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Livestock Manure Management Systems and Greenhouse Gases Production

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BACKGROUND

Agriculture is the source of three major "greenhouse gases", carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which contribute to the process of global warming, via the "greenhouse effect". Undoubtedly, livestock agriculture is also a source of these three gases, which result from the animal's inherent metabolic activity as well as a potential outcome of recycling of livestock manure as an organic fertilizer.

So far, current estimates of greenhouse gas (GHG) emissions from livestock agriculture are mostly crude estimates based on animal inventories, often with little regards to the specific management systems used (*e.g.* Desjardins and Mathur, 1997; Monteverde et al., 1997, Casada and Safley, 1990). Within the scope of the development of an action plan to reduce agricultural emissions of GHG, it is important to correctly appreciate the relative impact of the various components of manure management systems on the overall GHG emissions from livestock agriculture. Under the hypothesis that manure management is a major contributor to GHG emissions from livestock agriculture, it would be justified to promote the adoption of systems and practices known to emit less GHG or else stoke the R&D required to develop the appropriate technology.

This working document was prepared to provide a very quick outlook of the issues at hand relative to action planning for reducing GHG emissions in Canadian livestock agriculture by:

- presenting an inventory of manure management practices used for four major livestock and poultry productions;
- reviewing the processes involved in the production of GHG in the manure management stream;
- highlighting the information available of the GHG production in Canada in this respect, and;
- discussing the relevance or the need for additional R&D to evaluate or mitigate the production of GHG in livestock manure management systems.

This document is not the fruit of an exhaustive consultation or literature review on the above topic, as neither time nor resources were available to accomplish this task. Instead, this document should be regarded as a working paper to provide background information for the on-going debate on the contribution of manure management systems and practices to overall GHG emissions from livestock agriculture.

LIVESTOCK MANAGEMENT SYSTEMS IN CANADA

Table 1 presents the range of the components of most manure management systems used throughout Canada. Accurate data on the distribution of the currently used practices within specific manure management systems is scarce, even if we only wanted to discuss broad systems such as solid or liquid manure management systems. The 1995 Farm Inputs Management Survey (Census Canada, 1996)

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summarises few aspects of the manure management systems and practices used on some 2 000 farms in the major ecozones. The data presented in this last document unfortunately presents data aggregated over all livestock species, skewing the trends existing between contrasting livestock production approaches, for example solid manure management with beef vs. liquid manure management for swine.

TABLE 1: Typical components of a livestock manure management system in Canada.

Operation	Solids	Semi-Solid/Liquids
Collection	Gutter Cleaners Front End Loaders	Slotted Floors (complete with gutters) Scrapers cable hydraulic tractor
Transfer	Manure Wagons Open Tank Spreaders Dump Trucks Earth Moving Equipment	Pumps submerged, open impeller piston pneumatic Augers Vacuum Tank Wagon Pipeline Gravity Continuous Flow Gutters Large Diameter Pipes
Storage	Stockpile Bunk Silo	Glass Lined Steel Concrete Earthen
Treatment	Aerobic compost dry incinerate Anaerobic	Aerobic pre-storage partial total Anaerobic Solid/Liquid Separation
Utilize/Disposal	Land Application Energy Production (e.g. biogas)	Land Application Irrigation Energy Production

Short of having enough time to request a specific rerun of the 1995 farm input data from Census Canada, livestock specialists and engineers from few provinces were contacted to brush up a picture of the most common manure management practices in their respective province. While not all of them were able to respond in time, it is fair to assume that trends between Prairies provinces may be similar, as for the situation in Atlantic Canada or Central Canada, at least for the purpose of this working paper. Alternatively, requests could be made to Census Canada to better focus their upcoming survey round, to be conducted in the next one or two years. Further to this, very few Canadian livestock producers are presently using composting or other manure treatment processes (Table 1) as a component of their manure management system. This is why these options will not be dealt with in this document, in spite of the anticipated high GHG emissions rates with some processes.

Manure Management Systems and Storage

In short, manure management systems can be categorised in two broad class, solid and liquid (inclusive of semi-liquid systems) manure management systems, each being associated with different storage structures, handling and spreading equipment, etc... As well, modern production techniques have

optimised manure management systems for specific operational needs in most major livestock production sectors. For example, poultry broilers and beef cattle operations, when confined in feeding areas, are relying on some form of bedded manure packs, while swine producers mostly use liquid manure management systems.

Beef

In Western Canada, most cow-calf operations will overwinter cattle in more or less defined paddocks designed to serve both as feeding areas and protect cattle from winds; cow-calf operations would often confine their cattle to these paddocks for up to six months. Cattle feeder and finishing operations will feed larger animals into permanent feedyards. Manure is implicitly managed in solid form as bedded manure packs. In Central, Eastern and Atlantic Canada, beef cattle are also mostly raised on bedded manure packs, either outdoor, under shelters or in barns. Operations featuring outdoors exercise yards, feedyards or overwintering paddocks, must intercept and store runoff water from these areas in retention basins, and eventually spread it in nearby fields.

Upon yearly, seasonal or otherwise regular cleaning of the stalls, paddocks or pens, manure is either directly spread in the fields (no storage) or temporarily stockpiled for spreading at a later date. Windrow composting is a practice that seems to become popular with a small proportion of producers.

Dairy

Dairy production is probably the oldest "commercial" livestock production sector in the country, and presents a broader range of manure management systems and practices. After years of restructuration of this sector, most recent operations are larger and opt for liquid manure management systems (still mainly semi-liquid, here), featuring scrappers and appropriate structures (mainly concrete in newer operations). For example, in New Brunswick and Manitoba, over 30% of the operations would fit in this category. Noteworthy, the above 30% of the operations would account for a much larger proportion of the total milk produced provincially. The trend in Saskatchewan is probably similar to that in Manitoba, with newer operations moving towards liquid manure management in free-stall barns. This type of management is likely to be even more widespread in Québec and Ontario.

The smaller operations often still manage manure in solid form and pile it directly on the ground or apply it to fields on a nearly daily basis (as in most of Western Canada and New Brunswick). In Central Canada, the smaller operations will have a solid manure pile on the ground (is the case over 50% of the time) or on a concrete storage structure. When managed in liquid form, operations in Québec will usually have concrete storage structures, while 25% of the New Brunswick and Manitoba farms would have earthen manure storage structures (inclusive of "molehill" storage). Around 5% of the dairy operations in Manitoba and New Brunswick have concrete manure storage structures. Some very large operations have slatted floors with underfloor storage systems (2-5%).

Swine

Liquid manure management systems have greatly evolved over the last 30 some years in the swine industry. Today, over 90% of the hogs produced across Canada originate from barns managing manure

in liquid form. Over the years, bedded manure pack systems have grown in popularity with smaller producers, to rear feeder hogs and, sometimes, dry gilts.

While concrete storage structures are very common in Québec, the large majority (over 90%?) of all liquid manure storage structures used by swine producers in Manitoba, Saskatchewan and New Brunswick would be earthen manure storage structures. Very few, if not only older operations would feature underfloor storage structures. The few producers (less than 5%) using bedded manure packs, usually clean barns between each production cycle (approximately twice a year), to directly spread the solid manure in fields or temporary store it in a pile until it is spread.

Poultry

The poultry production sector comprises two production streams, namely the egg (inclusive of broiler egg hatching) and broiler productions. Liquid or semi-solid management systems are suited to the egg layers operations; broiler operations evolved around free roaming on bedded manure packs.

Solid manure from broiler operations is typically cleaned after each production cycle (6-7/year) to be temporarily stockpiled before spreading or else directly spread to fields. In New Brunswick, many operations seem to contract out the cleaning and trucking of poultry manure to other farms or even for other uses in and out of province (composting, etc...). Baring a growing popularity in "solid manure systems" where faeces are pressed or dried to near solid consistencies before leaving the poultry layer housing, most egg layers operations in Saskatchewan and New Brunswick use liquid manure management systems. These producers often have covered, concrete manure storage structures; the same system is used by approximately 50% of the egg producers in Manitoba. The other egg producers often have no storage structures per se, basically spreading the manure accumulated in a spreader every four to five weeks.

Land application of livestock manure

The options for spreading of livestock manure greatly depend on the solids content of the manure. Solid manure is most commonly broadcast applied at the surface with open top spreaders (box or side slinger types). The delay before incorporation of broadcast applied solid manure is very variable in many operations; when applied on pasture or prairies, it is not incorporated at all. Nearly all of the solid manure from beef cattle, poultry broilers and that from more than 50% of the dairy operations in the country is likely to be field applied in this fashion.

The options for liquid manure are a little broader, ranging from broadcast spreading to deep injection with a variety of equipment. The high solids content of dairy liquid manure (semi-liquid) is such that injection (deep or shallow) is a more difficult task, even when dilution water is added (*e.g.* milking parlor wastewater). For this reason, the large majority of the dairy operations managing manure in liquid form (*i.e.* about 30 to 40% of all operations) are expected to rely on conventional "splash plate" spreaders or side delivery spreaders to broadcast apply liquid manure. We can generalise that the same holds true for most egg producers. Again, manure applied in this fashion on annual crop's stubble in Western Canada is usually incorporated, as in other provinces when applied in the fall or early spring. When applied to pastures and prairies, there is no incorporation.

Liquid manure application practices used by swine producers are quite a bit more varied. A 1995 survey in Manitoba indicated that over 80% of the producers, who accounted for 50% of the market hog production, used conventional "splash plate" spreaders to broadcast apply liquid swine manure. Information from New Brunswick seems to indicate similar trends. Saskatchewan swine producers are said to use injection (10 to 15 cm) as a main land application technique in the industry. By and large, most recent and new operations are considering effective methods to reduce odours during land application, such as deep injection, shallow injection or dribble bar application equipment. In the light of the above and the ever increasing share of swine production originating from recent or new operations, we speculate that approximately 50% of the liquid swine manure volumes are currently applied with the latter methods across the country.

POTENTIAL SOURCES OF GHG IN THE MANURE MANAGEMENT STREAM

Very briefly, GHG can arise from some components of manure management systems when manure is allowed to develop partial or fully anaerobic conditions either via low oxygen availability or the predominance of anaerobic microsites on organic matter particles. Anaerobic bacteria essentially degrade manure solids into highly reduced compounds, inclusive of CH_4 and CO_2. GHG from livestock faeces can also be emitted directly from the trapped CH_4 and CO_2 in the faeces when going through the animals' lower intestine, but it is generally assumed that this source is usually accounted for in the livestock's enteric emissions (NGGIC, 1996a).

N_2O is also a potential GHG gas produced from manure, which may or may not evolve in aerobic conditions, as a result of the nitrification of NH_3 in NO_3^-, or in a subsequent oxygen deprived situation from the denitrification of the later via microbial activity. For this to occur over anyone of the components of a manure management system at the facility's level (within livestock housing or during storage), aerobic conditions must first prevail.

Table 1 indicate the three most common manure management system components, namely in-barn handling (gutters for temporary storage or daily scrapping, etc...), long term storage, and land application. The potential for GHG emissions from these three sources is discussed below, sometimes with reference to the overall emissions from livestock to provide a relative perspective. Note that much of the discussion gyrates around the production of CH_4 as a component of biogas, which implicitly includes the production of CO_2 in a 2:1 proportion. To simplify the discussion, we will assume that little opportunities for aerobic microbial activities exist when conditions are favourable to anaerobic digestions, and vice versa. This implies that manure decomposition in the livestock housing or in the storage will either result in CO_2 and N_2O (when aerobic conditions prevail) or a biogas containing CH_4 and CO_2.

In-barn emissions of GHGs

By and large, most of the nitrogen found in manure is in the form of NH_3 and associated compounds and organic nitrogen (proteins and microbial biomass). As little or no NO_3^--N is present in fresh manure, the potential for nitrification is almost negligible (and following denitrification), unless the manure is purposely aerated in some ways, which intuitively lead us to assume little opportunities the production

of N_2O from fresh manure.

Solid manure management in the barn

In the case of solid manure management, the two systems commonly in use are gutters with daily evacuation (older dairy operations) and bedded manure packs (poultry broilers, beef cattle and some swine). In the case of daily evacuation, it is quite unlikely that the microbial biomass would have time to adapt to its "new" environment to maintain a notable metabolic activity between excretion time and evacuation to the storage structure.

Most poultry broiler operations use enough litter material to keep a very dry bedded manure pack (around 25 % moisture content), so dry as to inhibit an efficient composting activity. Consequent to such aerobic conditions, it is unlikely that significant CH_4 would be emitted from these operations. However, these conditions may be favourable to nitrification and denitrification processes, leading to N_2O emissions along with CO_2. For instance, Lavoie et al. (1995) report N_2O concentrations of 2 to 12 ppm (0.3 to 0.6% of the CO_2 concentrations in the housing) over bedded manure packs in swine feeder barns (where moisture contents are higher than poultry litter), where the deep litter was frequently mechanically aerated to favour "in-barn composting". Note here that bedded manure packs are not aerated in most livestock operations. Thus, it is likely that bedded manure packs systems may be the origin of some N_2O emissions, in particular when used for swine and egg laying operations since aerobic conditions are often present, as a result of the dry bed conditions maintained for optimum livestock production.

The case of bedded manure packs for cattle production is treated below, as the large majority of cattle operations in Canada are based on outdoor feedyards, overwintering paddocks and pastures.

Liquid manure management in the barn

Most liquid manure management systems involve shallow gutters with weekly to by-weekly evacuations of manure to the storage. Some systems feature a small pre-storage structure collecting the manure into a central pumping station. Semi-liquid systems may be managed such as to have daily scrapping (*e.g.* dairy, newer egg layer operations with belt conveyors), less frequent cleaning (*e.g.* tractor cleaning in free stall dairies, shallow pits in egg layer operations) or long term storage underfloor storage under slotted floors. As the manure moisture content will generally be around 70% for poultry and above 85% (dry basis) for other livestock, anaerobic conditions are likely to prevail in fresh manure. Patni and Jackson (1996) concluded that exhaust air from barns with either underfloor storage for an egg layer operation (12 months storage) or shallow gutters (weekly evacuation) was not significantly enriched in CH_4. While some amounts of anaerobic decomposition undoubtedly occurs within confined livestock housing, as demonstrated by pungent and complex odours emanating from these operations, the amounts of CH_4 and CO_2 produced as a result of anaerobic fermentation could be very small. CIGR (1994) considers that CO_2 production from manure in barns is always smaller than 4 % of livestock's enteric production in France.

GHGs emissions from manure storage systems

To abbreviate the discussion of GHG emissions from outdoor storage and feedlot bedded manure packs, these two different components of manure management systems will be treated in this section. Partial manure decomposition occurs during storage, via both limited aerobic and anaerobic processes, yielding either mostly CO_2 or mixtures of CH_4 and CO_2. We also propose that N_2O emissions is not likely a significant issue at this stage of the manure management, contrary to the predictive work of Monteverde et al. (1997). The rationale for this is that the bulk of the manure in large manure storage systems is subjected to mostly anaerobic conditions, and hence limits the nitrification of NH_3 into NO_3^-, a necessary process which may lead to N_2O production. This issue will be visited again in the following discussion section.

GHGs from bedded manure packs

Very few Canadian studies focused on GHG emissions from solid manure systems. For beef cattle, a study suggest that in US, less than 0,2 % of the CH_4 potential emissions may be produced as a result of anaerobic fermentation in wet areas of feedlot pens (Lodman et al., 1991). The same study indicates that between 0.1 to 3% of the total CH_4 volume that could be produced in a digester (.24 to .33 m^3kg^{-1} of dairy or cattle manure's organic matter, for example) could be emitted if the temperature in the pack was allowed to reach 30°C. In summary, the CH_4 emissions from beef cattle feedyards, overwinter areas for cow-calf operations and sheltered bedded packs would be, at the most, of the order of magnitude of that cited in the US study. It is likely to be even less under our cooler climate, in agreement with Casada and Safley (1992) who assumed a 2.5 times lower CH_4 production from beef cattle operations in Canada relative to US.

By and large, no NO_3^- are found in cattle manure from feedyards or overwintering paddocks (T. Gilson, Norwest Labs, personal communication 1998). While this may at best be regarded as indirect evidence,

it would support the appreciation that little opportunities for N_2O emissions from this manure source as well.

GHGs from liquid manure storage structures

After a nearly 10 year R&D program on biogas energy recovery from livestock manure, Agriculture and Agri-Food Canada essentially concluded that Canada's climatic conditions does not favour economically viable biogas recovery from outdoor storage structures (Van Die, 1987). As most of the past work in Canada on biogas generation focused on fully or partially enclosed digester designs, we cannot use these results to estimate potential CH_4 emissions from outdoors storage structures. Patni et al. (1995) found that biogas production (27% CH_4) from dairy liquid manure stored in an outdoor concrete storage amounted to no more than 15 L/day/cow over the summer months in Ottawa. Fragmented data indicate that biogas production would be close to negligible over the winter. Whereas their study was conducted over a single manure batch, with the reservation than slightly higher values are anticipated with continuous addition of fresh manure, Jackson et al. (1994) concluded that biogas production rates found with dairy liquid manure over the warmer part of the year in Ottawa was approximately 10 times less than the values reported for biogas recovery from manure storage structures in more temperate climate. Further to this, Patni et al. (1995) suggest that CH_4 emissions from stored dairy manure is not likely to be a significant contributor to GHG emissions from dairy operations, as it amounts to only 3% of the enteric production from dairy cows. When accounting for Canada's cooler climate, these values are not necessarily in contradiction with the higher values obtained under controlled, high temperature conditions, such as the work of Martinez et al. (1995): these high values could occur for very short period of time during the summer in Canada.

Little information is available for manure from other livestock species where manure is managed in liquid form. Ross and Moser (1997) suggest that biogas recovery from liquid manure in earthen storage structures will not be economically viable for regions north of Kansas (or latitudes greater than 40°).

GHG from solid manure piles

Two main type of solid manure are stored in piles, namely "dry" solid manure from poultry broiler and hog operations using bedded manure packs operation and "wet" solid manure, as typically from smaller dairy operations. Manure from poultry broiler operations shows moisture contents between 25 and 40%, which is low enough to entertain aerobic conditions but too low for strong microbial activity, as would be sought for composting. Manure from swine operations on bedded manure packs may show higher moisture contents, however. At any rate, manure from most broiler and swine operations on solid manure is stored in piles for only a short period of time over the winter. Hence, little CO_2 production is expected from this manure type, unless it is windrowed and allowed to pick up moisture.

Manure piles from dairy operation (molehill storage or pile on the ground) will have moisture contents in excess of 80%, which is not conducive to the development of vigorous aerobic microbial activity. If any, the main decomposition process during storage would be via facultative anaerobic microbial activity in microsites around the organic particles in the manure. Conversely, Desjardins and Mathur (1997)

propose relatively high CH_4 emission rates from solid manure storage on the basis of an internal report by Pattey et al. In spite of this report, which we did not have time to obtain, and whereas some partial anaerobic activity undoubtedly occurs, we would propose that CH_4 emissions from solid manure such as that from dairy operations would even be less than that reported by Patni et al., (1995) for liquid manure storage of dairy manure. As well, limited opportunities for N_2O emissions are thought to exist in large storage structures, where little nitrification seems to occur.

Thus, both CH_4 emissions from solid manure storage are likely to be even less important than those presumably associated with liquid manure storage structures, and could be even less than 3% of enteric production and respiration of ruminants (Patni et al., 1995). This last comparison may however show much greater values when discussing the case of the proportion of CH_4 emissions from stored manure for non-ruminant species such as swine, an apparent source of confusion between different data sources.

GHGs from land application of manure

Livestock manure can be "applied" to field via two main processes, namely as a result of direct defecation by grazing livestock in pastures or else by spreading stored manure. Relative to the direct application of fresh manure and recalling that fresh manure will present moisture content higher than 80%, conditions for anaerobic production of CH_4 would apparently exist. However, research indicates that rapid drying following excretion in a pasture situation would considerably limit potential for CH_4 evolution, down to levels of less than 1% of the potential CH_4 production from the same manure (Lodman et al., 1991).

However, land application of stored manure (over short or longer term) is the component of Canadian livestock manure management systems where N_2O emissions is an important issue. The greatest contribution of livestock manure to N_2O is likely to originate from recycling manure as a source of nitrogen fertilizer, where the organic nitrogen and NH_3 is first mineralised into NO_3^- to be later partially denitrified when conditions are conducive to this fate. Consequently, many approaches to estimating N_2O from land applied livestock manure are closely modelled around the approaches developed for N_2O emissions from the use of inorganic fertiliser (*e.g.* NGGIC, 1996b).

Most current predictions do not account for the application method or timing of livestock manure (*e.g.* NGGIC, 1996b; Monteverde et al., 1997). Some work is in progress in Saskatchewan on the comparative N_2O emissions between commercial fertilisers and livestock manure, which should clarify this issue to some extent. One major management difference that may exist vs. livestock manure management as a fertiliser source may be the tendency for fall application of manure as a convenient manure management option. This may lead to opportunities for mineralization and denitrification prior to the winter and in early spring. Work from Chen et al. (1995) suggests that very high emission rates may be incurred from agricultural soils during freeze-thaw cycles.

DISCUSSION

The work of Desjardins and Mathur (1997), largely based on OECD data and estimates, suggest that over 20% of the CH_4 emissions from livestock may originate from manure. The work of Martinez et al. (1995) and Sauvant (1995), and our incomplete perusal of recent work in this area lead us to

conclude that the coefficients used by Desjardins and Mathur (1997) definitely need to be revised, as microbial activity in manure storage structures in Canada are most likely in the order of 10% of that expected in more temperate countries, where their data seem to originate from. The disagreement between these points of view is a stumbling block to address in the development of an action plan vs. manure storage structure *i.e.* "Is manure handling and storage an issue or not?" In summary, we are tempted to conclude that CH_4 emissions from stored livestock manure in Canada may not be significant. In retrospect, large errors can creep into estimates of GHG emissions when emission factors developed in other countries are used to represent emission potential from manure storage structures and practices in Canada. We thus propose that CH_4 emissions from manure handling systems and manure storage structures in Canada is not a major contributor to overall GHG emissions from livestock.

For N_2O emissions from manure handling and storage, we question the prediction of N_2O emissions from manure storage structures proposed by Monteverde et al. (1997), who attribute equal emissions from manure storage structures and land application (*i.e.* each accounting for 13% of the total N_2O production from agriculture). NGGIC, 1996b did not retain this as a notable source of N_2O emissions in Australia. Further, very little Canadian data can support this prediction which paints manure storage structures as major contributor to N_2O emissions. Data should be obtained to either confirm or infirm these estimates, or else a thorough literature review should be conducted to establish the potential for significant emissions of N_2O from mostly anaerobic manure storage structures in northern climates.

Thus, many questions need to be answered before a GHG reduction plan can be developed and successfully implemented for livestock agriculture. We suggest the following interim actions as milestones along the development of a GHG action plan for this sector. To a lesser extent, the following actions should be considered:

Taking the necessary steps to ensure that the next farm survey to be conducted by Census Canada will yield more useful data to estimate GHG emissions from livestock production;

Establishing the CH_4, CO_2, and N_2O emission rates over the entire duration of manure storage across a wide range of livestock manure types and under our various climatic conditions;

Investigating the potential CH_4, CO_2, and N_2O emissions from bedded manure packs when used in barns, as this management practice is currently promoted as an environmentally sound manure management system;

More importantly, an action plan to reduce GHG emissions from livestock manure should be principally focused on N_2O emissions from land application. Many of the actions devised to reduce N_2O emissions from commercial fertiliser use could well apply here. It may be relevant to investigate the contribution of common land application practices such as fall manure application vs. springtime and injection vs. broadcast spreading.

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REFERENCES

Casada, M. E. and L.M. Safley Jr. 1990. Global methane emissions from livestock and poultry manure. Biological and Agricultural Engineering Dept., North Carolina State University, Box 7625, Raleigh, NC 27695-7625. 124pp

Census Canada. 1996. Farm Inputs Management Survey, 1995. Statistics Canada catalogue no. 21F009XPE. 47pp.

Chen, Y., S. Tessier, A.F. MacKenzie and M.R. Laverdiere. Nitrous oxyde emission from an agricultural soil subjected to different freeze-thaw cycles. Agric., Ecosyst. & Envir. 55 :123-128

CIGR. , 1994. Aerial Environment in Animal Housing - Concentrations in and Emissions from Farm Buildings. *Workings Group Report Series* - n° 94.1 : 116 p.

Desjardins, R.L., S.P. Mathur. 1997. Agroecosystem greenhouse gas balance indicator: methane component – Technical report: Net methane emissions from agroecosystems in Canada for the years 1986 and 1991. Report no. 21. Agri-Environmental Indicator project. Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Central Experimental Farm, Bldg 74, Ottawa, ON K1A 0C6. 19pp.

Jackson, H.A., N.K. Patni, D.I. Masse, R.G. Kinsman, M.S. Wolynetz, D.J. Buckley, J.A. Munroe, F.D.

Sauer, R. Desjardins, and E. Pattey. 1994. Measuring greenhouse gas emissions from dairy manure slurry. ASAE paper 944540. Am. Soc. Of Agr. Eng., 2950 Niles Rd, St-Joseph, MI 49085-9659

Lavoie, J., Marchand, G., J.Y. Drolet and Y. Gingras. 1995. Biological and chemical contamination of the air in a grower-finisher pig building using deep litter systems. Can. Agr. Eng. 37(3):195-204

Lodman, D.W., M.E. Branine, B.R. Carmean, P. Zimmerman, G.M. Ward and D.E. Johnson. 1991. Estimates of methane emissions from manure of U.S. cattle. Report from the Metabolic Laboratory, Dept of Animal Sciences, Colorado State University, Fort Collins, CO 80523. 17 pp.

Martinez J, Guiziou F, Gueutier V. 1995. Emissions de méthante au cours du stockage des déjections animales. *CEMAGREF Rennes*. Rapport de fin de contrat INRA-CEMAGREF N° 2710 A, : 20 p.

Monteverde, C.A., R.L. Desjardins and E. Pattey. 1997. Agroecosystem greenhouse gas balance indicator: nitrous oxyde component – Technical report: Estimates of nitrous oxide emissions from agroecosystems in Canada for the years 1986 and 1991 using the Revised 1996 IPCC/OECD Methodology. Report no. 20. Agri-Environmental Indicator project. Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Central Experimental Farm, Bldg 74, Ottawa, ON K1A 0C6. 29pp

NGGIC, 1996a. Workbook for livestock – Workbook 6.1. Prepared by the National Greenhouse Gas Inventory Committee, Canberra, Australia. 113 pp
www.environment.gov.au/portfolio/esd/climate/ggi/natmethod/agriculture6/agriculture6.html

NGGIC, 1996b. Workbook for non-carbon dioxide gas from the biosphere – Workbook 5.1. Prepared by the National Greenhouse Gas Inventory Committee, Canberra, Australia. 24 pp
www.environment.gov.au/portfolio/esd/climate/ggi/natmethod/agriculture5/agriculture5.html

Patni, N., H. Jackson, D. Masse, M. Wolynetz and R. Kinsman. 1995. Greenhouse gas release from stored dairy-cattle manure slurry. In: Proceedings of the Seventh International Symposium on Agricultural and Food Processing Wastes. Am. Soc. Of Agr. Eng., 2950 Niles Rd, St-Joseph, MI 49085-9659

Ross, K.F. and M.A. Moser. 1997. AsSTAR Handbook – A manual for developing biogas systems at commercial farms in the United States. United States Environment Protection Agency report EPA-430-B-97-015, EPA AgSTAR program, 401 M St SW (6202J), Washington, D.C. 20460, USA

Sauvant D. 1995. Les émissions de méthane par les ruminants. In: Perrier A. (coord.). *Agriculture et gaz à effet de serre*. Dossier de l'environnement de l'INRA N° 10. INRA, Paris, 7-15.

Van Die, P. 1987. An assessement of Agriculture Canada's anaerobic digestion program. Engineering and Statistical Research Centre report I-933. May 1987. 73 pp.